

# ULTRASONIC METHODS OF TEXTURE MONITORING FOR CHARACTERIZATION OF FORMABILITY OF ROLLED ALUMINUM SHEET

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## INTRODUCTION

Texture (preferred orientation) has a significant influence on the formability of metals. This was shown experimentally for rolled steel sheet by Stickels and Mould [1]. They found a correlation between the in-plane angular variation of r-value and the anisotropy of Young's modulus, E, as measured by ultrasonics. The r-value is a measure of plastic strain on deep drawing, defined as  $\epsilon_{yy}/(\epsilon_{yy} + \epsilon_{zz})$ , with  $\epsilon_{yy}$  the in-plane strain and  $\epsilon_{zz}$  the strain in the thickness direction.

The theoretical basis for the correlation between r-value and E was established by Davies, Goodwill and Kallend [2]. They showed that, for moderate textures in cubic metals, plastic anisotropy can be predicted from values of the orientation distribution coefficients (ODC), which are coefficient multipliers in the series expansion for the orientation distribution function (ODF). In particular, only the zeroth and fourth-order ODC contribute to plastic anisotropy, as measured by r-values.

The orientation distribution function (ODF) gives the probability that a single crystal in the rolled plate will have its crystallographic axes at Euler angles  $\zeta$ ,  $\psi$ ,  $\phi$  to axes embedded in the plate. The ODF,  $\omega$ , can be expressed in a series of generalized spherical harmonics  $Z_{lmn}(\theta)$  where  $\theta = \cos \zeta$  [3]:

$$\omega = \sum_{l=0}^{\infty} \sum_{m, n=-l}^l \omega_{lmn} Z_{lmn}(\theta) e^{i(m\psi + n\phi)}$$

where the  $\omega_{lmn}$  are the orientation distribution coefficients.

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Davies et al., showed that Young's modulus could be expressed in terms of  $\omega_{4m0}$ , where  $m = 0, 2, 4$ . Consequently, both plastic and elastic anisotropy are affected (for moderate texture) by the same ODC, which explains the correlation of r-values with E.

Recently, Sayers [4] has shown how the velocities of bulk ultrasonic waves can be related to ODC. He finds that the velocities depend only upon the three  $\omega_{4m0}$  for polycrystalline aggregates of cubic metals displaying macroscopic orthorhombic symmetry. This result has been extended to guided waves in thin plates by Thompson and his co-workers [5, 6] and to surface waves by Delsanto et al. [7]. All of these theories neglect effects such as alloying content, dislocations and inclusions. The velocities are assumed to be calculable from single-crystal moduli, weighted by the ODF and averaged over all possible orientations.

In this work we consider the use of various ultrasonic techniques for texture monitoring in rolled aluminum alloy sheets. We have measured the ODC on sheets obtained from actual production runs of a commercial alloy used for can stock. We made measurements with different transducers and velocity measurement systems at different laboratories. These measurements were compared as an internal consistency check on the ultrasonic theories. We also made an independent check by obtaining the ODC from neutron diffraction pole figures. Finally, we looked for a correlation of ODC with measurement of formability in the sheets.

#### EXPERIMENTAL CONSIDERATIONS

The test plan followed in making ultrasonic measurements of ODC is shown in table I. Two different methods were used to obtain each of the ODC. For example, to obtain  $\omega_{420}$  the method of acoustic birefringence was used.  $\omega_{420}$  was also obtained by measuring the difference of arrival times of the lowest-order symmetrical Lamb-mode ( $S_0$ -mode), propagating parallel and perpendicular to the rolling direction. Both EMATs and piezoelectric transducers were used to measure birefringence; EMATs were employed with a time-interval-averaging system (T.I.A.), and piezoelectric transducers with pulse-echo-overlap (P.E.O.).

For measurement of  $\omega_{440}$ , we used differences of arrival times of the lowest-order symmetrical shear-horizontal mode ( $SH_0$ -mode); waves were propagated parallel and at  $45^\circ$  to the rolling direction.  $\omega_{440}$  was also obtained from the angular variation of the  $S_0$ -mode; here the average of the arrival times of guided waves propagated parallel and perpendicular to the rolling direction was subtracted from arrival time of a guided wave propagated at  $45^\circ$ . The exact forms of the equations used to calculate ODC from arrival times can be found in Refs. [4-6].

We note that  $\omega_{420}$  and  $\omega_{440}$  can be obtained from relative arrival time (or relative velocity) measurements, as described above. In contrast  $\omega_{400}$  must be obtained from an absolute velocity measurement. This is because  $\omega_{400}$  represents a contribution to texture which is invariant under rotation about the plate normal.

In addition to ultrasonic measurements, the (200) and (111) neutron diffraction pole figures were made on the NBS reactor. The theory used to obtain ODC from pole figures is outlined in Ref. 8, and details of measurement technique are given in Ref. 9.

Table 1. Methods, transducers, and velocity measurement systems used by various laboratories to obtain  $\omega_{400}$ .

| <u>ODC</u>     | <u>METHOD</u>          | <u>TRANSDUCER</u> | <u>SYSTEM</u> | <u>LAB</u>  |
|----------------|------------------------|-------------------|---------------|-------------|
| $\omega_{420}$ | BIREFRINGENCE          | EMAT              | T.I.A.        | NBS         |
|                |                        | PIEZOELECTRIC     | P.E.O.        | NBS         |
|                | $S_0$ -MODE            | EMAT              | T.I.A.        | NBS<br>AMES |
|                | NEUTRON<br>DIFFRACTION |                   |               | NBS         |
| $\omega_{440}$ | $SH_0$ -MODE           | EMAT              | T.I.A.        | AMES<br>NBS |
|                | $S_0$ -MODE            | EMAT              | T.I.A.        | AMES<br>NBS |
|                | NEUTRON<br>DIFFRACTION |                   |               | NBS         |
|                |                        |                   |               |             |
| $\omega_{400}$ | $SH_0$ -MODE           | EMAT              | T.I.A.        | AMES        |
|                | $S_0$ -MODE            | EMAT              | T.I.A.        | AMES        |
|                | NEUTRON<br>DIFFRACTION |                   |               | NBS         |
|                |                        |                   |               |             |

Measurements were made on 8 sheet specimens of hot-rolled 3004 aluminum alloy having gage thickness of 3 mm. These specimens were cut from the end of a coil that had an approximate diameter of 2 m. All measurements were done at room temperature.

Measurements on six of the sheets were done both with the sheet in the as-received (curved) configuration, and also in a flattened (small curvature) configuration. Flattening was done without introducing any plastic deformation. Two of the sheets were run through a small rolling mill to reduce curvature.

For the  $S_0$ ' and  $SH_0$ -mode measurements, two transducers (transmitter and receiver) were kept at a fixed separation as measured along the sheet. For curved sheets, this necessitated a flexible fixture between transducers. A typical path length between transducers was in the range of 20-40 cm. Arrival times were measured with precision on the order of a few ns over these pathlengths.

Acoustic birefringence measurements were made with pulse-echo transducers having apertures of approximately 1 cm<sup>2</sup>. Shear wave arrival times were typically measured with echoes arriving about 30-40  $\mu$ s after generation of a toneburst in the transducer. Arrival time precision were typically of the order of a few ns.

Formability was characterized by deep drawing. Blanks were cut from the coil and deep-drawn to can shape. Because of plastic anisotropy, the

top of the drawn material will not be a circle, but will have a lobe structure, or "ears."

#### ULTRASONIC RESULTS

We show in Fig. 1 the relation between formability and  $\omega_{420}$ . Formability is in arbitrary units. For six of the sheets the ODC is the average of  $\omega_{420}$  obtained with both the NBS and Ames  $S_0$ -mode systems; for two of the sheets, the Ames data were used, since the NBS system had not been developed at the time these sheets were available for test. We found that values of  $\omega_{420}$  obtained by NBS and Ames were generally in good agreement; the spread in values was about 10 percent of the mean for sheets measured at both labs.

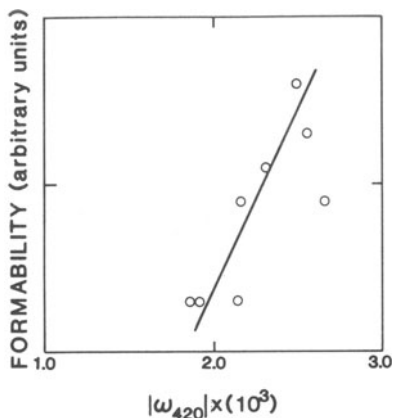


Fig. 1. Relation between formability and  $\omega_{420}$  measured with  $S_0$ -mode.

A straight line can be drawn so that the value of  $\omega_{420}$  for seven of the eight sheets falls within  $0.2 \times 10^{-3}$  of the line. One plate has a value of  $\omega_{420}$  which falls off the line by about  $0.5 \times 10^{-3}$ . At this time, we are unsure whether this outlier is due to measurement error, or due to lack of a high correlation between  $\omega_{420}$  and formability.

For simplicity, we assume that a measure of the uncertainty in our results is the amount that our outlying point departs from this line. This results in an uncertainty in  $\omega_{420}$  of  $0.5 \times 10^{-3}$ . We estimated the effect of this uncertainty has in predicting formability from measurement of  $\omega_{420}$ . This estimation requires use of the actual formability values, which are proprietary to the supplier so we are unable to give specific details here. However, the result of our estimation procedure is that a prediction of formability can be made from measurement of  $\omega_{420}$  with an uncertainty comparable to errors in the (destructive) measurement of formability by deep drawing.

A comparison of  $\omega_{420}$  as measured with  $S_0$ -mode and with birefringence showed that the birefringence measurements are usually somewhat higher than the  $S_0$ -mode values; however, the overall trend of increasing formability with  $\omega_{420}$  is apparent in both data sets. A regression fit of a straight line to the birefringence data would have approximately the same slope as a line fitted to the  $S_0$ -mode data.

The correlation between  $\omega_{440}$  and formability is not as encouraging as with  $\omega_{420}$ . This is shown in Fig. 2, where most of the data can be fitted reasonably well to a straight line, except for one outlying data point that is far removed from the others. This anomalous point is not associated with the same sheet which gave the outlying point in Fig. 1.

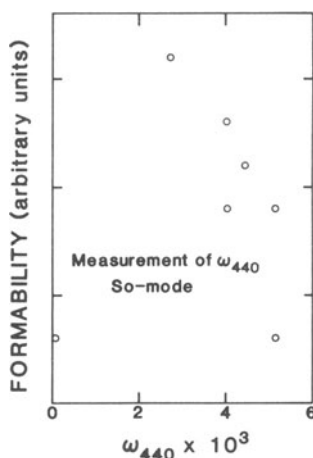


Fig. 2. Relation between formability and  $\omega_{440}$  measured with  $S_0$ -mode.

The data in Fig. 2 are the average of Ames and NBS measurements of  $\omega_{440}$  using the  $S_0$ -mode technique (same as method used to generate Fig. 1). Data obtained with the  $SH_0$ -mode technique at both labs gave  $\omega_{440}$  values in good agreement with those shown in Fig. 2. In particular, the  $SH_0$ -mode data showed that the outlying data point in Fig. 2 was not an artifact of the measurement technique. It is necessary to use different EMATs to generate the  $S_0$ -mode and  $SH_0$ -modes, so essentially the same data were obtained with four different sets of transducers. At present, we have no explanation for the outlying point in Fig. 2.

We also characterized the effect of sheet curvature on ultrasonic measurements. The results are shown in Fig. 3, where  $\omega_{420}$  is measured with the NBS  $S_0$ -mode system with the sheet as-received (curved) and with

the sheet clamped to a flat surface. There is a constant shift between the values, with the ODC measured in the flat configuration being about 10 percent higher. We note that this 10 percent change in ODC corresponds to a change of arrival times of only about 15 ns for the acoustic pathlength used in this experiment. This is equivalent to a pathlength change of 0.1 mm between clamped and unclamped geometries. Liftoff, however, can also influence the apparent arrival time; we will return to this point later.

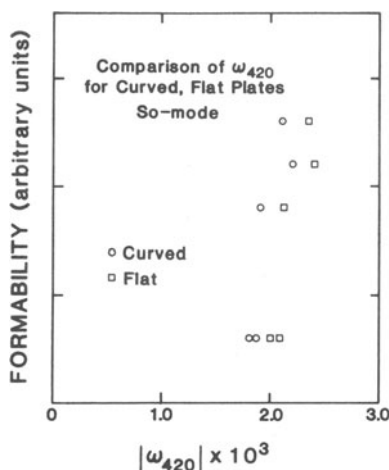


Fig. 3. Comparison of  $\omega_{420}$  as measured on curved and flattened plates with  $S_0$ -mode.

The fact that the same trend of formability versus  $\omega_{420}$  is found for the flat and curved geometries means that, in a practical (i.e., production) sense, it should still be possible to correlate ultrasonic measurements of  $\omega_{420}$  with formability.

All the techniques used to obtain  $\omega_{420}$  and  $\omega_{440}$  were based on measurement of relative velocity. To obtain  $\omega_{400}$ , it is necessary to make absolute velocity measurements [5, 6]. We found that values of  $\omega_{400}$  obtained from  $S_0$ -mode and  $SH_0$ -mode were not in agreement. Possible sources of error are: dispersion (in  $S_0$ -mode), inability of the mathematical theories to model the effect of texture on ultrasound with a required accuracy, and also error propagation associated with absolute velocity measurements.

#### COMPARISON OF NEUTRON DIFFRACTION AND ULTRASONIC MEASUREMENTS

Neutron diffraction measurements were made on samples cut from one corner of each of five sheets. The average of ODC obtained from the (200) and (111) pole figures were taken. Details of the measurement procedure can be found elsewhere in these proceedings [9]. Here we are interested only in comparison of neutron diffraction and ultrasonic measurements of ODC.

For  $\omega_{420}$ , we calculated the average of all  $S_0$ -mode and birefringence data taken on each of the plates. For six of the plates, we had four ultrasonic measurements: two from  $S_0$ -mode, and two from birefringence (see table I). For the remainder we took the average of one  $S_0$ -mode and two birefringence measurements. We treated each ultrasonic measurement as an independent event, and calculated the mean value and standard deviation of  $\omega_{420}$  for each plate. The standard deviation of  $\omega_{420}$  thus defined was about  $0.2 \times 10^{-3}$  for all plates.

The average  $\omega_{420}$  are plotted in Fig. 4, which shows that the neutron diffraction values are somewhat higher, by about  $0.1 \times 10^{-3}$ ; this shift in ODC is indicated by the dashed line in the figure. Because there is little scatter of the points about this shifted line, we think that neutron diffraction and ultrasonic values of  $\omega_{420}$  correlate well (agree to within a constant term).

We performed a similar analysis for  $\omega_{440}$  and found that in general the neutron diffraction values were higher. There was, however, less correlation between values; i.e., less tendency for a constant shift between values. From a practical viewpoint, this may be relatively unimportant for texture monitoring, since it appears that ultrasonic monitoring of  $\omega_{420}$  may be the method of choice.

The neutron diffraction values of ODC for the plates which gave outlying points in Figs. 1 and 2 essentially reproduced the ultrasonic results. This means that these anomalous values of ODC are not artifacts of the ultrasonic techniques.

In fact, a plot of neutron diffraction values of  $\omega_{420}$  versus formability would closely replicate Fig. 1, with essentially the same slope but a different intercept.

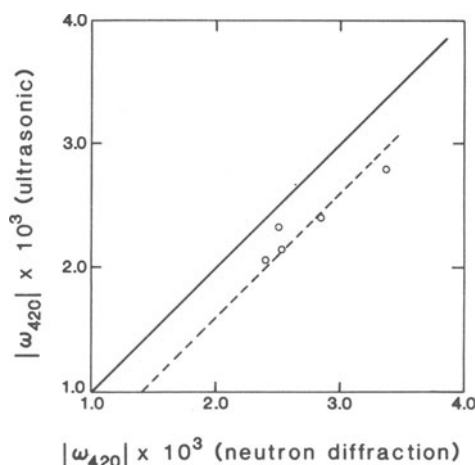


Fig. 4. Comparison between ultrasonic and neutron diffraction values of  $\omega_{420}$ .

## EXTENSION TO ON-LINE TEXTURE MONITORING

The ultrasonic measurements were all done in a static, off-line mode in laboratory conditions. Practical (on-line) measurements may require rapid measurement as sheet is being rolled with velocities in the range of tens of km/h. On-line operation demands rapid ODC measurements with good precision. This in turn requires a good signal/noise ratio.

For on-line operation, the transducer of choice may be the EMAT because of its ability to generate ultrasound in metals without an acoustic couplant. There are, however, certain problems peculiar to EMATs which must be overcome for the intended application.

EMATs have intrinsically lower transduction efficiencies than piezoelectric transducers. EMATs are susceptible to liftoff; the transduction decreases exponentially with distance from the workpiece [10]. Furthermore, the arrival time also depends on liftoff.

A system which may prove capable of on-line operation is currently under development. It consists of EMATs to generate and receive the  $S_0$ -mode. The transmitting EMAT is driven by a MOSFET current pulser which can deliver up to 140 A into a low-impedance load. The amplifier operates in a gated burst mode from about 250 kHz-1 MHz. The receiving EMAT is matched to a low-noise tuned preamplifier/amplifier that has a narrow bandwidth (about 50 kHz). The amplifier can be tuned through the same frequency range as the current pulser, and has a gain of as much as 80 dB.

We have measured both the change in signal amplitude and in arrival time with liftoff for this EMAT system. We found a steep rise in apparent arrival time change with liftoff. As expected from theory [8], the liftoff causes an exponential decay in signal. This indicates the need for either carefully controlling liftoff, or having a sensor to measure liftoff and using an arrival time correction.

The system can achieve an arrival time precision of  $\pm 1$  ns with 1 mm liftoff by averaging over 100 arrival times. Because the transmitter can operate at a pulse repetition frequency of about 100 Hz, a measurement of arrival time having the desired precision ( $\pm 1$  ns) can be obtained every second. This may be sufficiently rapid for on-line operation.

## CONCLUSION

Three ODCs relate to both formability and ultrasonic velocity for rolled sheet of cubic metals. We made ultrasonic and neutron diffraction measurements to determine ODC on plates obtained from production runs of 3004 aluminum alloy plates. Relative velocity measurements were used to obtain  $\omega_{420}$  and  $\omega_{440}$ ; absolute velocities were measured to obtain  $\omega_{400}$ .

Values of  $\omega_{420}$  and  $\omega_{440}$  as measured by relative velocity techniques in different laboratories were in good agreement. There was also generally good agreement between ultrasonic and neutron diffraction measurements of  $\omega_{420}$  and  $\omega_{440}$ . Values of  $\omega_{400}$  obtained by  $S_0$ -mode and  $SH_0$ -mode were not in good agreement.

Comparisons of ODC with a formability measure were made. A good correlation was found between  $\omega_{420}$  and formability. Most of the data showed a small scatter about a straight-line fit of the data; only one point was somewhat off this straight line.



From a practical point of view, it seems that the uncertainty in prediction of formability based on fitting the  $\omega_{420}$  is acceptable. That is, the estimated error in formability based on ultrasonic measurement of  $\omega_{420}$  is comparable to the estimated error in the direct measurement of formability from deep drawing.

It appears that EMATs will be the most practical means of on-line texture measurement. EMATs were simpler and faster to use in laboratory tests than dry-coupled piezoelectric transducers. They can also launch plate modes without the wedges and couplant necessary with piezoelectric devices.

Some of the problems associated with on-line use of EMATs have been addressed. The decay of signal amplitude and change in apparent signal arrival time with liftoff were measured. A good S/N was found for liftoff as large as 1 mm. Liftoff sensors may be required to correct for arrival time changes for liftoffs greater than 0.5 mm.

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